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The mechanical properties of Fe-Co heterogeneous alloys fabricated by powder metallurgy techniques

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Fe–Co heterogeneous alloys fabricated by powder metallurgy techniques were hot rolled, cold rolled and then heat treated. These processes produced a type of fibre-reinforced composite which consisted of fibrous Fe and Fe–Co phases. The tensile strength of the alloys depended on the composition and degree of order of the Fe–Co phase. The rule of mixtures was applicable, provided that the dependence of strength in the Fe–Co phase on Co content was considered.

1. Introduction

The alloys which combine high strength with toughness often have a kind of duplex structure such as that of 6% Ni steel [1], piano wire [2] etc. Two-phase alloys which have a high strength phase and a tough or ductile phase are expected to have the desired combination of high strength and toughness or ductility and these alloys are usually prepared by heat treatment [3]. Other methods of preparation include melting two or more elements which are unable to dissolve one another, and the sintering of powders. It is also reported that each phase of a two-phase alloy is converted to fibre by mechanical working and a kind of fibre-reinforced composite is obtained [4] [5]. Fe–Ag [6], Fe–Cu(–X) [5] [7–9], metal–glass [10], Pd–Ga–Cu [11], whose components are unable to dissolve one another, have all been investigated.

In this paper, Fe and Co powders, which are able to dissolve each other, were sintered at elevated temperatures and as a result, Fe, Fe–Co and Co phases were obtained in sintered Fe–Co alloys. They were hot rolled and cold rolled, so that Fe–(Fe–Co) two-phase fibrous alloys were fabricated and their mechanical properties were investigated.

2. Experimental

Starting materials for this experiment were atomized Fe powder (−100 mesh) ASC100.29 supplied by Höganäs Corp., and ground Co powder (−100 mesh). Chemical compositions are given in Table I. The Fe powder was mixed with Co powder for 2 h by a ball mill along with an additive element powder. The mixed powder was compacted in a double-ram, floating die, whose walls were lubricated with stearic acid, carbon tetrachloride mixture. Every pressing was done at 5 t cm^{-2}. The pressings were 100 mm long, 15 mm wide and 15 mm thick and contained 10 to 30 vol % Co, or 2 vol % additive element and 20 vol % Co. They were subsequently sintered at 950° C for 2 h in purified hydrogen atmosphere. The sintered alloys were heated at 900° C in hydrogen atmosphere, then hot rolled to 1.8 mm thick plates and subsequently cold rolled to 0.5 mm thick plates.

Cold rolled plates were annealed in evacuated silica capsules at temperatures above the order–disorder transition temperature of FeCo (50 : 50) alloy ($T_c \doteqdot 720°$ C) so as to make Co diffuse into Fe phase and produce a maximum degree of disorder in the Fe–Co phase. Then they were

TABLE I Chemical compositions of powders (wt %)

	C	Si	Mn	Cu	S	Fe	Co	Ni
Fe powder	0.005	0.003	0.023	0.004	0.004	–	0.026	0.031
Co powder	0.033	0.024	0.009	0.029	0.014	0.43	–	0.14

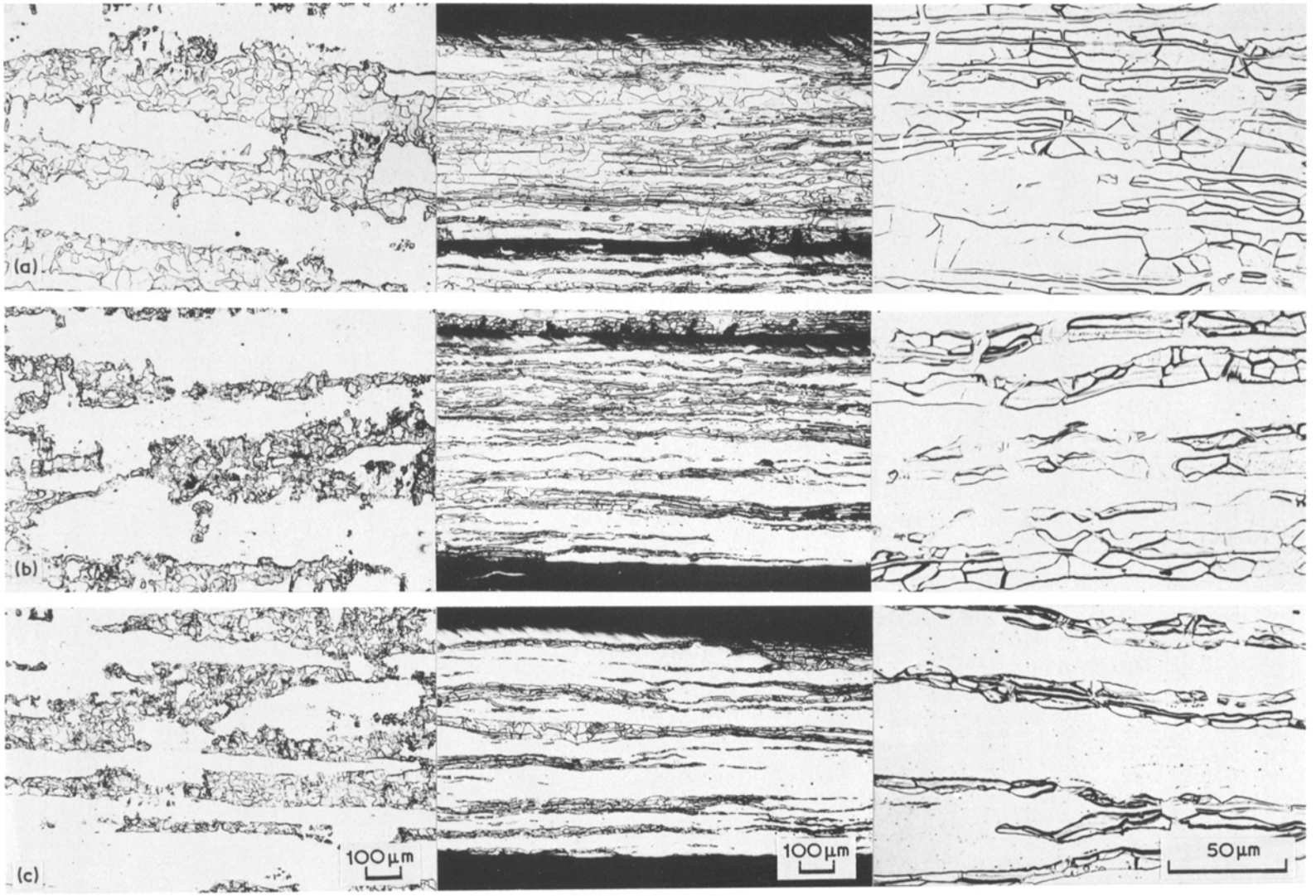

Figure 1 Typical duplex structure of rolled specimens which were annealed at 950° C for 1 h with the longitudinal section and surface parallel to the rolling direction: (a) 10 · Co, (b) 20 · Co, (c) 30 · Co.

quenched into ice water. They were subsequently heated for 1 h at various temperatures in the range 370 to 520° C, and again quenched into ice water in order to produce various degrees of order in the Fe–Co phase [12].

Tensile test specimens were cut parallel to the rolling direction, with a gauge length of 16 mm and a cross-sectional area of about 0.5 x 4 mm^2. The tensile test was carried out at room temperature using a Instron-type universal testing machine driven at a constant cross-head speed of 0.2 mm min^{-1}.

3. Results

3.1. The structure of Fe–Co heterogeneous alloys

Fig. 1 shows a typical duplex structure of rolled specimens which were annealed at 950° C for 1 h. The Fe–Co phase is not attacked, while the Fe phase is attacked to bring out grain boundaries by 3% nital. Both Fe and Fe–Co phases are elongated parallel to the rolling direction. In Fe–10% Co, the vol % of Fe phase is large, while it is considerably smaller in Fe–30%Co. An example of line analysis by an electron probe microanalyser is shown in Fig. 2. Fe–Co phase contains about 20 to 40%Co in specimens annealed at 950° C, and Co phase hardly remains (Fig. 3). Fe–Co phase of specimens annealed at higher temperatures, contained a smaller content of Co, whereas in specimens annealed at lower temperatures, Co phase remained in some cases and vol% of Fe–Co phase was smaller.

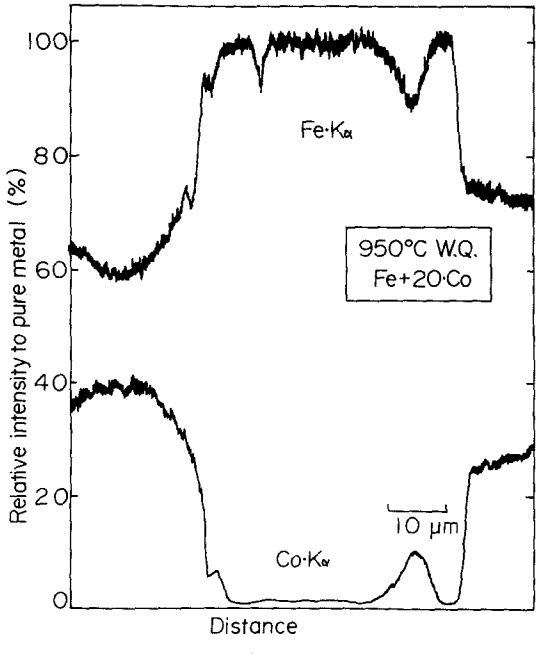

Figure 2 Linear analysis by an electron probe microanalyser. (Fe–Co specimens were annealed at 950° C and then quenched into ice water.)

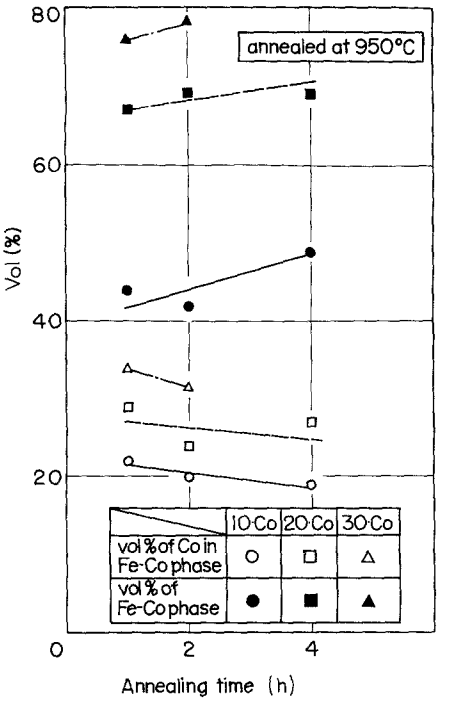

Figure 3 The relation between volume fraction of Fe–Co phase and Co in Fe–Co phase and heating time at 950° C. (Specimens were annealed at 950° C and then quenched into ice water.)

3.2. The effect of heat treatment on mechanical properties

Fig. 4 shows the relation between yield strength and tensile strength and ageing temperature in specimens annealed at 950° C for 1 h: both increased with increasing Co content. The yield strength of the specimens was virtually independent of the ageing temperature but the tensile strength increased with raising the ageing temperature. These trends became more marked for greater Co content. The yield strength and the tensile strength for specimens annealed at 800 or 1100° C are given in Fig. 5. The yield strength of specimens annealed at 1100° C decreased as the ageing temperature was raised, but the tensile strength decreased when specimens were aged at 520° C. In general, tensile strength was greater in specimens annealed at 950° C, than in those annealed at 800 or 1100° C. Considering that the degree of order of FeCo (50 : 50) alloy increases as the ageing temperature is raised [12], it be concluded that the

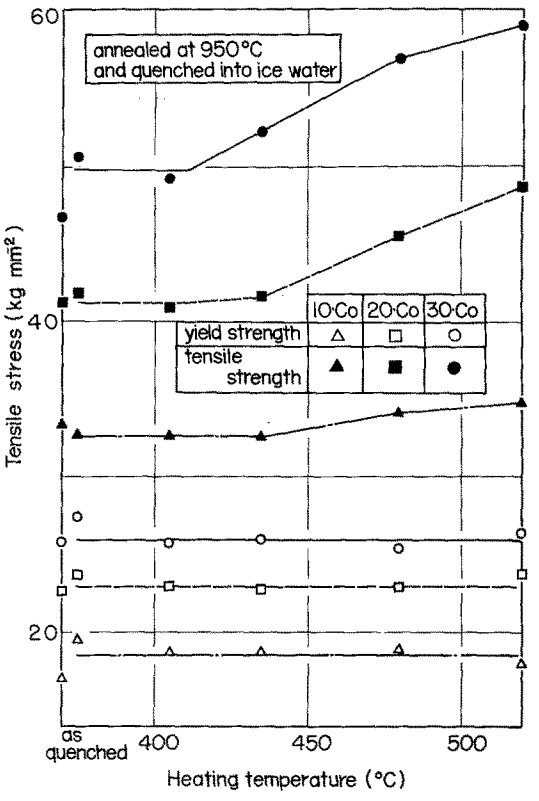

Figure 4 Ageing temperature dependence of tensile strength. (Specimens were annealed at 950° C for 1 h and quenched into ice water.)

tensile strength increases with the degree of order of Fe–Co phase.

Fig. 6 shows the relation between elongation and ageing temperature in specimens annealed at 950° C for 1 h. In as-quenched specimens, the elongation was not so great as in specimens aged at 375 ° C or so, and it decreased the higher the ageing temperature. In particular, specimens of Fe–30% Co which was aged at temperatures above 480° C fractured without necking. Fig. 7 shows a similar relation for specimens annealed at 800 and 1100° C for 1 h: the elongation is larger in specimens annealed at 800° C than in those annealed at 950 or at 1100° C.

In specimens quenched into ice water, dimples were observed on the fracture surface, irrespective of Co content, whereas in specimens aged at 520° C, the fracture surface consisted of dimple profiles and cleavage facets. The fracture surface was largely made up of dimples in Fe–10% Co and of cleavage facets intermingled with dimples in the Fe–30% Co.

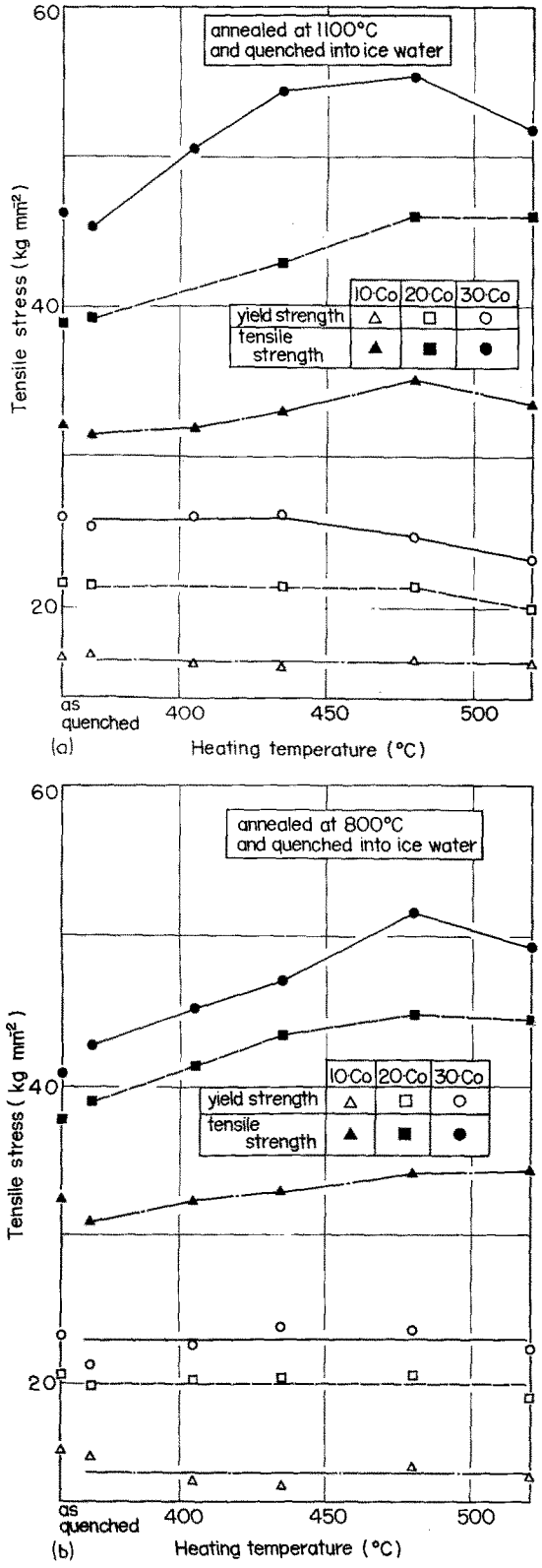

Figure 5 Ageing temperature dependence of tensile strength. (a) Specimens were annealed at 1100° C for 1 h and quenched into ice water. (b) Specimens were annealed at 800° C for 1 h and quenched into ice water.

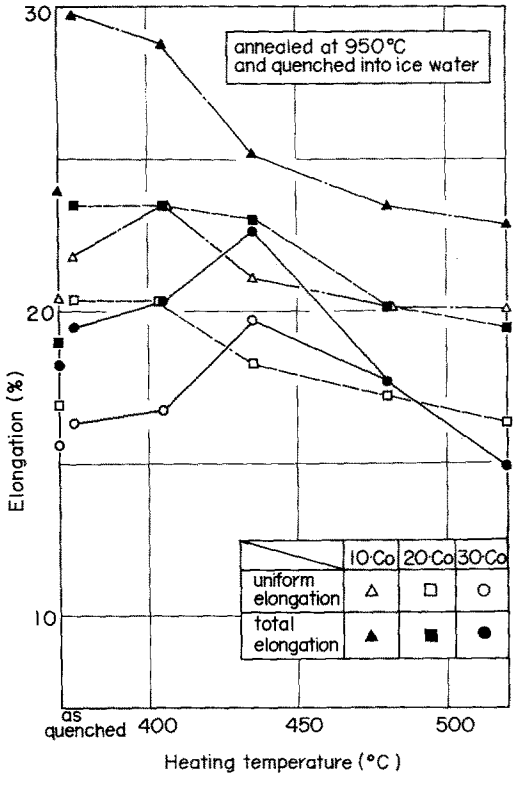

Figure 6 Ageing temperature dependence of elongation. (Specimens were annealed at 950° C for 1 h and quenched into ice water.)

3.3. The effect of additive elements on the mechanical properties

It was reported that the ductility of FeCo (50 : 50) alloy is affected by additive vanadium [13]. We investigated the effect of other additive elements on the mechanical properties of Fe–20% Co specimens (Table II). Both the yield strength and the tensile strength of alloys containing additive elements were higher than those of pure Fe–Co heterogeneous alloys in as-rolled and as-quenched specimens. In aged specimens, Zr and Mo raised the strength of Fe–20% Co, but Nb, Ti and Ta had the reverse effect, especially on the tensile strength. Additive elments decreased the elongation of all the specimens. These results indicate that Ti, Ta and Nb are unsutiable for improving mechanical properties of Fe–Co heterogeneous alloys.

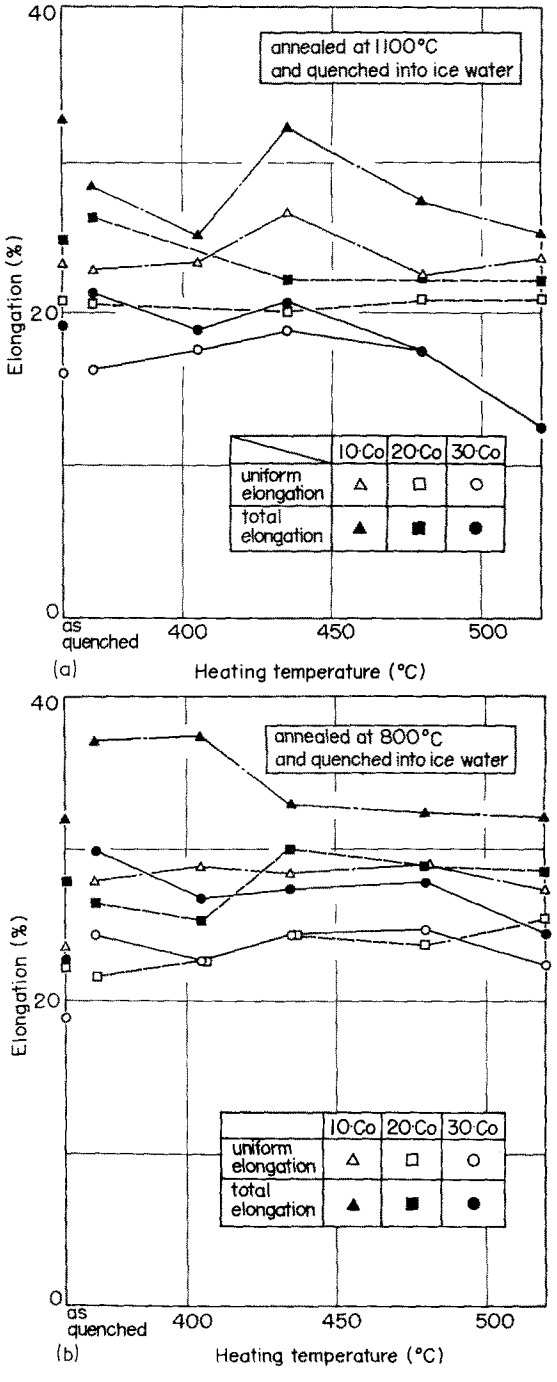

Figure 7 Ageing temperature dependence of elongation. (a) Specimens were annealed at 1100° C for 1 h and quenched into ice water. (b) Specimens were annealed at 800° C for 1 h and quenched into ice water.

4. Discussion

4.1. The effect of heat treatment on the strength in tensile test

Fig. 4 and 5 indicate that both the yield strength and the tensile strength have a maximum value when Fe–Co alloys consist of an Fe phase and an Fe–Co phase containing intermediate Co content. When specimens were annealed at temperatures as low as 800° C, the Co phase still remained and the vol% of Fe–Co phase was small. In those specimens, the yield strength and the tensile strength were relatively low, while the elongation was re-

TABLE II The effect of additive elements on the mechanical properties of Fe–20% Co specimens

Element	Heat treatment	Yield strength ($MN\,m^{-2}$)	Tensile strength ($MN\,m^{-2}$)	Uniform elongation (%)	Total elongation (%)
Zr	as-rolled	853.6	879.1	–	0.4
	as-quenched	285.2	452.8	10.9	13.5
	aged at 520° C	312.6	518.4	–	12.8
Mo	as-rolled	797.7	882.0	–	1.7
	as-quenched	288.1	486.1	13.5	16.8
	aged at 520° C	275.4	527.2	12.8	13.6
Nb	as-rolled	712.5	782.0	–	1.1
	as-quenched	235.2	394.0	11.0	14.0
	aged at 520° C	217.6	422.4	–	12.4
Ti	as-rolled	775.2	813.4	–	1.1
	as-quenched	278.3	410.6	10.0	13.5
	aged at 520° C	226.4	384.2	9.0	10.8
Ta	as-rolled	698.7	714.4	–	0.4
	as-quenched	261.7	425.3	16.5	19.8
	aged at 520° C	266.6	425.3	–	13.9
10% Co*	as-rolled	563.5	597.8	1.0	3.5
20% Co*	as-rolled	682.1	705.6	0.9	2.2
30% Co*	as-rolled	745.8	780.1	1.0	1.6

* Pure Fe–Co heterogeneous alloys

latively large. This is because Fe–Co alloys hardly have a high strength second phase, i.e. Fe–Co phase.

When the specimens were annealed at 1100° C, Co diffused into the Fe phase and the vol% of Fe–Co phase with small Co content was large, both the yield strength and the tensile strength were relatively low and the elongation was small. This is because these Fe–Co alloys have a large vol % of relatively soft second phase, i.e. Fe–Co phase containing small Co content, and because the aged Fe–Co phase fractures by cleavage before any plastic instability appears. Specimens aged at about 450° C have a maximum value of the tensile strength (Fig. 5), because Fe–Co phase aged at this temperature is difficult to fracture by cleavage. Ageing temperature affects both the tensile strength and the elongation, but not the yield strength (Fig. 4). This result is inconsistent with the other result for FeCo (50 : 50) alloy [14], in which the yield strength of FeCo (50 : 50) in compression testing decreased as the degree of order increased. It seems, therefore, that the Fe phase and/or the interphase boundary between Fe and Fe–Co phases may play a significant role in determining the yield strength in the same manner as the flow stress of two-phase alloys is affected by the secondary phase and/or the interphase boundary, as reported by Ashby [15].

4.2. The effect of Co content on the tensile flow stress

In specimens annealed at elevated temperatures, Fe-Co and Fe phase were seen to be elongated parallel to the rolling direction, so that the specimens used could be regarded as a kind of fibre-reinforced composite (see Fig. 1). Therefore, the authors treat Fe–Co heterogeneous alloys as fibre-reinforced composites, and assume a rule of mixtures.

Let the volume fraction of the Fe–Co phase be V_s. Then, the volume fraction of the Fe phase is given by $(1 - V_s)$. The tensile flow stress σ_c of the composites is given by

$$\sigma_c = \sigma_s \cdot V_s + \sigma_{Fe} \cdot (1 - V_s), \qquad (1)$$

where σ_s and σ_{Fe} are the tensile stress of the Fe–Co phase and the Fe phase at the strain produced by σ_c in composites, respectively. In specimens annealed at 950° C, the volume fraction of Fe–Co phase is as shown in Fig. 3. Fig. 8 shows the relation between tensile flow stress and volume fraction of Fe–Co phase. Therefore, Equation 1 does not seem to hold in specimens annealed at elevated temperatures. This is because the Co content in the Fe–Co phase also depends on the volume fraction of Co in these alloys and the strength of the Fe–Co phase also depends on the Co content in that phase.

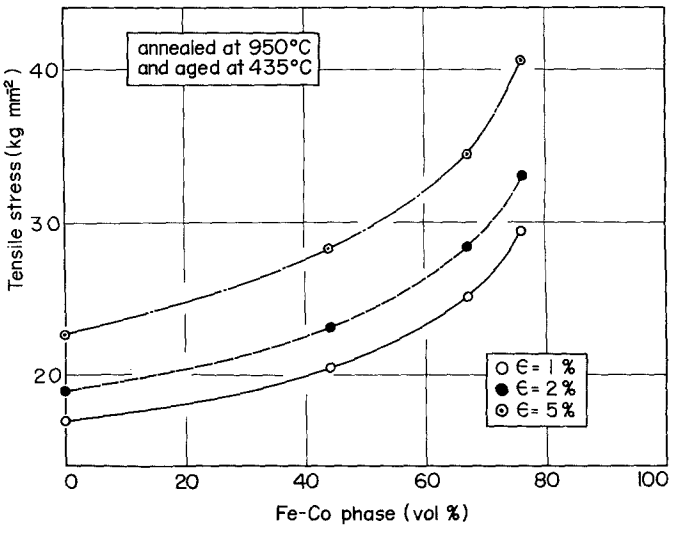

Figure 8 The relation between tensile flow stress and volume fraction of Fe–Co phase. (Specimens were annealed at 950° C and then quenched into ice water, followed by ageing at 435° C for 1 h.)

It is reported that the flow stress of Fe–Co alloys increases linearly with Co content in compression testing when the Co content of homogeneous Fe–Co alloys is lower than 50 at.% [14]. Assuming that a similar relation holds for the tensile flow stress, and considering that σ_s is equal to the flow stress, σ_h, of FeCo (50 : 50) alloy when the Co content is equal to 50 at.%, the following relation holds

$$\sigma_s = \sigma_{Fe} + 2 \cdot (\sigma_h - \sigma_{Fe}) \cdot C, \qquad (2)$$

where C is the atomic concentration of Co in homogeneous Fe–Co alloys. The following equation can be obtained from Equations 1 and 2;

$$\sigma_c = \sigma_{Fe} + 2 \cdot (\sigma_h - \sigma_{Fe}) \cdot C \cdot V_s. \qquad (3)$$

In specimens annealed at elevated temperatures, the average Co content of the Fe–Co phase is lower than that for FeCo (50 : 50) alloy. σ_h is calculated from Equation 3, and σ_s is estimated using Equation 3, as well. In this experiment, the volume fraction of these Fe–Co alloys is V_{os}, the relationship between V_s, C and V_{os} is expected to be given by

$$V_s \cdot C = V_{os}. \qquad (4)$$

Fig. 9 shows the relationship between $V_s \cdot C$ and V_{os} in specimens annealed at 950° C. $V_s \cdot C$ does not depend on the annealing time, and $V_s C \fallingdotseq 0.9 V_{os}$. Thus Equation 4 may be written as

$$V_s \cdot C = K \cdot V_{os}, \qquad (4')$$

where K is a constant which is nearly equal to 1.

The following equation can be obtained by substituting Equation 4′ into Equation 3,

$$\sigma_c = \sigma_{Fe} + 2 \cdot K \cdot (\sigma_h - \sigma_{Fe}) \cdot V_{os}. \qquad (5)$$

The relation between σ_c and V_{os} is expected to give straight lines. Fig. 10 gives the relation between σ_c and V_{os} in specimens annealed at 950° C. The calculated flow stress σ_h, of FeCo (50 : 50) phase is obtained from the slope of these lines.

Fig. 11 shows the relation between the calculated flow stress σ_h, and ageing temperature in specimens annealed at elevated temperatures. σ_h

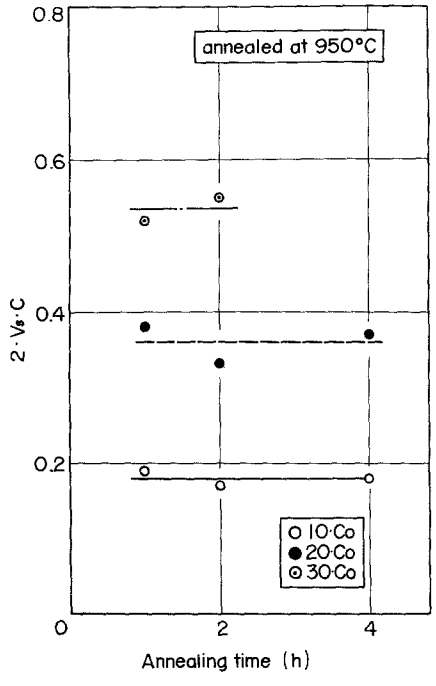

Figure 9 The dependence on annealing time of $2V_s \cdot C$. (Specimens were annealed at 950° C and then quenched into ice water.)

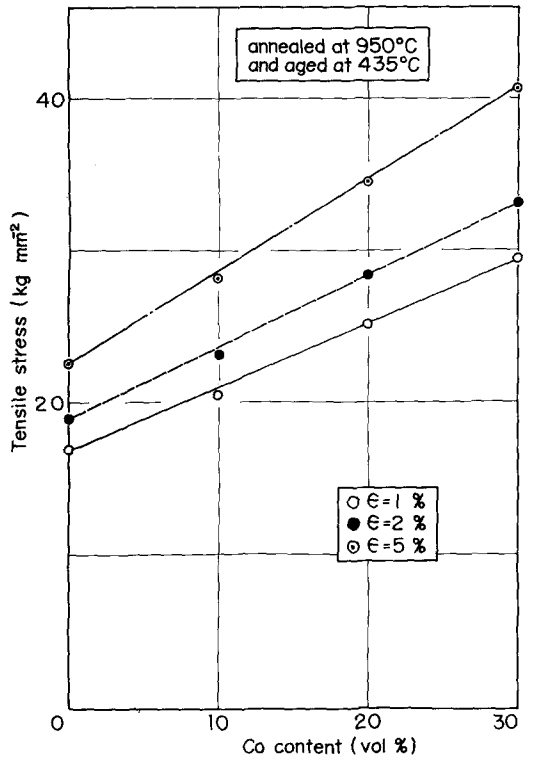

Figure 10 The relation between tensile flow stress and volume fraction of Co, V_{os}. (Specimens were annealed at 950° C for 1 h and quenched into ice water, followed by ageing at 435° C for 1 h.)

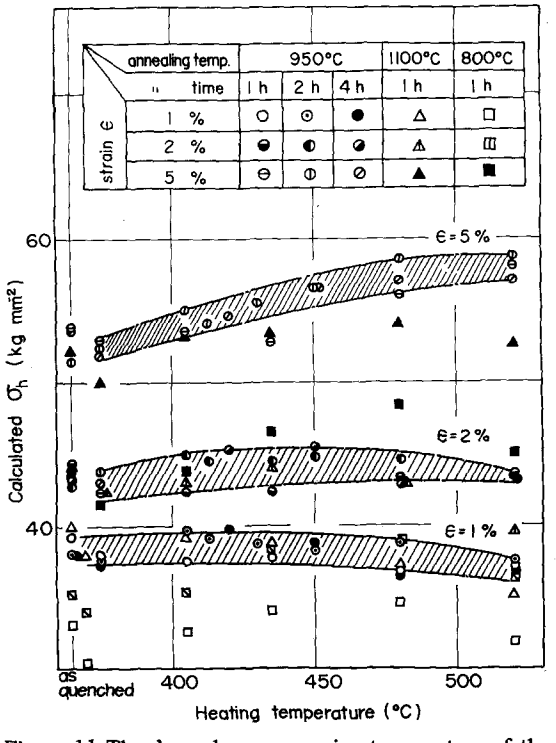

Figure 11 The dependence on ageing temperature of the calculated flow stress, σ_h. (parameter ϵ represents strain.)

hardly varies with annealing time at 950° C, but it does vary with the annealing temperature. σ_h is lower in specimens annealed at 800° C than those annealed at 950° C. This is because the Co phase, as well as the Fe phase, remains existent so that the volume fraction of Fe–Co phase is small in specimens annealed at 800° C, and thus the product $V_s \cdot C$ is not as large as expected from Equation 4.

σ_h calculated for specimens annealed at 1100° C is nearly equal to σ_h calculated for those annealed at 950° C, except the specimens were aged at temperatures above 480° C where the ordered Fe–Co phase seems to fracture by cleavage during uniform deformation. This is surmised from the fact that a lot of acoustic emission signals were detected when specimens aged 520° C were deformed uniformly, and from observing that Fe–Co phase aged at this temperature fractured by cleavage.

From these results, Fe–Co heterogeneous alloys produced by powder metallurgy techniques can resonably be regarded as kinds of fibre-reinforced composites consisting of Fe and Fe–Co phases, and therefore the ordered Fe–Co phase is expected to raise their tensile strength.

5. Conclusions

(1) Fe–Co heterogeneous alloys, which were produced by powder metallurgy techniques were hot rolled, cold rolled and then heat treated. This process resulted in a kind of fibre-reinforced composite alloy which consisted of Fe and Fe–Co phases.

(2) Their maximum tensile strength was obtained when the Fe and Co diffused mutually and the Fe–Co phase with appropriate Co content was formed. This happened when these alloys were heated for 1 h at 950° C. When most of the Co diffused into the Fe phase producing more homogeneous Fe–Co alloys, or when the Co hardly diffused into the Fe phase, their strength was lower than for those heat treated in the most appropriate condition. Therefore, the heat treatment has to be selected deliberately.

(3) Their tensile flow stress depended on isothermal ageing temperature for ordering the Fe–Co phase, and in general, it increased when the Fe–Co phase was ordered. However the tensile strength of specimens annealed at 1100° C decreased when they were aged at temperature of 520° C, and had a maximum when they were aged at about 450° C. That is because the ordered Fe–

Co phase tends to fracture by cleavage during tensile deformation.

(4) A rule of mixtures was found to hold for these Fe–Co heterogeneous alloys consisting of Fe and Fe–Co phases, provided the strength dependence of the latter phase on Co content was taken into account.

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